SERVO CONTROL SYSTEM FOR 45 METER DIAMETER PARABOLIC ANTENNA FOR GMRT

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Abstract

The 45 meter diameter antennas for the Giant Meterwave Radio Telescope (GMRT)require a precise position control system so as to achieve pointing and tracking accuracy of 30 arcsec rms. This paper describes the implementation of the system using three nested control loops. Concept of counter torquing required to eliminate the dead band effect due to the large backlash prsent in the drives,which use high reduction ratio gear boxes,is explained in detail. The results of tests carried out of one of the antennas during the installation are presented as a case study.

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1.0 **INTRODUCTION:** The Giant Meter Wave Radio Telescope,an aperature - sysnthesis array consisting of 30 fully steerable parabolic dishes of 45 diameter each,is being set-up about 80 Km north of Pune as a national facility for front line research in radio astronomy [1].Motion of these giant antennas needs to be controlled by a precision servo system so as to achieve rms tracking and pointing accuracy of 1/2 arc min. This paper describes implementation details and control system philosophy used for the servo system. General requirements and specifications are covered in Section 2. Section 3 highlights mechanical drive system and mount for the antenna.

Section 4 describes control system for the antenna, which employs three nested control loops. Tuning and installation procedure is described in Section 5. Section 6 presents a practical example of the tuning procedure by discussing the test results obtained during installation of one of the antennas.

2.0 GENERAL REQUIREMENTS AND SPECIFICATIONS FOR GMRT SERVO SYSTEM

The servo systems driving radio telescopes must meet two major requirements [2] :

2.1 High pointing accuracy

2.2 Ability to point any where in the sky

It is required to point the telescope within ± 10 % of the 3 dB radio beamwidth for a given wavelength which demands high pointing accuracy.

The second requirement is generally met by using a suitable two axis mount.Although an equatorial mount is always preferable,for large antennas like GMRT an altitude/azimuth (alt/az) mount is used owing to practical difficulties encountered with an equatorial mount.

In alt/az mount ,the antenna can be moved along two axes,viz: Azimuth (normal to the horizon) and Elevation (parallel to the horizon).It must be able to rapidly move itself from any given position to the radio source to be observed. (This motion is known as slewing). As it points towards the desired position of the source,the antenna should accurately track it so as to cancel the effect of apparent movement of the source due to the earth's rotation.

Table I gives specifications for the servo system.

(Note that normal operation is allowed upto 40Kmph wind speed. Once the wind exceeds this value and a storm tends to build up,the antenna is brought to zenith position of the elevation axis and is stowed by locking of the elevation bull gear by two lock pins driven by battery operated electric motors.)

3.0 MECHANICAL STRUCTURE and DRIVE SYSTEM.

3.1 Parabolic Dish

In order to meet both budgetary and technical requirements a novel design based on an innovative concept nicknamed SMART-(Stretched Mesh Attached to Rope Trusses) has been adopted for the dish antennas.[1]Basically very low weight and solidity are achieved in this concept by replacing the conventional back-up structure in a dish by a series of rope trusses stretched between radial parabolic frames.The reflecting surface is formed by employing a low solidity wire mesh stretched over the rope trusses. (Fig.1 shows sectional elevation of the parabolic dish.)It can be shown [1] that the overall wind forces and rotational moments of the 45 metre dish based on the SMART concept are similar to the moments of a 22 metre dish of conventional type surface with solid panels. This allows use of all drive components with much lower torque ratings resulting in considerable economy.

3.2 Mount for the Antenna

The radial parabolic frames which support the SS wire mesh are connected to a central hub .The hub is further connected at four points to an intermediate structure known as cradle.The cradle is mounted on the yoke top at two elevation bearing points .The elevation bull gear is placed in a plane perpendicular to the bearing axis and also attached to the cradle structure.

The two elevation bearings which support the cradle and the hub,are held by the two horns of the yoke structure.The yoke itself is supported on a single slew ring bearing for rotation about azimuth axis.The slew ring bearing in turn is held by a machined steel ring bolted to the top slab of the RCC tower.

A schematic representation of the Drive system is shown in Fig.1 & 2.

4.0 CONTROL SYSTEM FOR THE DRIVE.

4.1 Basic Block Diagram

The control system for the drive consists of the standard three nested loop configuration. This configuration allows independent tuning of the parameters of the three loops viz. the torque loop which is the inner most loop,velocity loop in the middle and position loop which is the outer most one. Adequate care is taken to set band width of each loop sufficiently greater than its adjacent outer loop, thereby ensuring that poles of inner loops do not affect the frequency response of the outer loops.

The block diagram of the Servo system is shown in Fig 3. Any variations in the antenna position as sensed by the encoder is fed to the position loop. The computer controlled position loop generates an error signal on comparing the input with the commanded position and feeds the error signal to the velocity loop. The velocity loop compares this signal with the tacho outputs of the motors and provides input to the torque loop after processing the signal through speed controller for the two motors. The error signal is compared with the actual current value of the motor and the torque loop drives the controller so as to effect corrections in the current flow to bring the position error to a minimum.(In a permanent magnet DC motor, the control of armature current flow results in torque variation.) In our case the torque loop output controls the firing angle of the SCR bridge for controlling the current through the motor.

4.2 Concept of Counter-Torquing

Large gear reductions are used in telescope drives to meet the low speed requirements for continuously tracking the celestial objects. These large reductions in the gears introduce backlashes in movement of the shafts. A dead band effect is noticed in the output shaft which is held stationary when the input shaft is rotating especially in the low speed regions. Such backlashes are effectively controlled using counter torquing techniques as described below :

Several methods are employed to overcome the backlash effect, which are known as counter-torquing methods [2].

For the GMRT servo system,the counter-torquing system uses two drive units consisting of motor,controller, gear-box and a pinion. The schematic arrangement has been shown in Fig. 5 & 6 . The two drive pinions are coupled to a common bullgear which drives the load.At no load torque conditions, both the pinions are opposing each other, exerting equal and opposing torques. When the torque demand changes in either direction, torques exerted by both the pinions change accordingly to exert net torque which is the algebraic sum of both the torques. This system ensures that both the pinions remain stiffly pressed on the respective bull gear teeth, therby eliminating the backlash.

4.3 Detailed Block Diagram

Fig.6 shows the detailed block diagram indicating the individual loops.It can be noted that two seperate current loops constitute the counter torquing system . The following paragraphs describe the functions of the loops.

4.3.1 Position Loop .

A 17 bit absolute encoder senses instantaneous antenna position giving angular resolution of 10 arc sec.Desired position is fed to the servo computer by the master computer as required by the user.The servo computer consists of 8086 CPU based computer control system.It computes instantaneous position error every 100 msec and feeds it to a compensator algorithm.The compensator algorithm implements a type I transfer function of the form

$$G_2(s) = [G_{22} (1+T_{21}s)/s(1+T_{23}s)] \qquad \text{..........1}$$

The digital compensator uses Tustin transformation [4] to transform above ` s ' domain transfer function to the ` z ' domain.The corrosponding difference equation is then solved in real time to implement the recursive filter.All the filter coeficients are calculated on-line from the gain and time constants entered by the user.

{It may be noted that an additional integration is involved in the velocity loop (integral of velocity is position) will make the over all system as type II system.The type II system will ensure zero error for ramp inputs.(Position trajectory during tracking could be considered as series of ramp inputs.)}

The gain and time constant values of the transfer function are entered during installation through a hand held terminal and are stored in an Electrically Erasable PROM for non-volatility.

Within the position loop as formed within the servo computer, all computations are done using integer plus fraction representation.The angles are, therefore, represented as 16 bit integer (degrees) and 16 bit fraction (fractions of degrees).Numbers are internally scaled so as to optimally use the dynamic range of the number system.DAC of 16 bit resolution is used for achieving the required linearity.

4.3.2 Velocity Loop:

The velocity loop is common for both the counter torque drives.It senses both the speeds and controls average of both the speeds.Speed feedback is derived from tacho meters provided with the servo motors.The tachos produce a DC voltage proportional to the motor speed.The velocity loop controller uses a lead -lag compensator.The lead network is included in the tacho feed back path, boosts the low frequency forward gain necessary for good steady state accuracy. The output of the velocity loop serves as the common torque command to the both current loops.Two separate current commands are generated by adding and subtracting a fixed DC bias from the common command.(i.e for a commanded torque of Tc,velocity output corrosponds to Tc/2; with a fixed bias ` b ',Tc/2 +b and Tc/2-b commands are generated. Both the torques algebraically add together to give the net torque Tc as commanded.)

4.3.3 Current Loop

The current loop consists of the current loop compensator,thyristor four quadrant convertor and DC servo motor(see fig.6).The current loop compensator consists of a PI controller giving good steady state accuracy.The thyristor convertor consists of a fully controlled,three phase half wave,four quadrant,fully regenerative thyristor bridge.Four quardrant operation enables a motor to act as a generator thereby exerting an opposing torque in the counter torquing arrangement.Regenerative braking ensures quick reversal of the motor.

The DC servo motor used is of permanent magnet type (Model TT 53810-B from M/s Industrial Drives ,USA).It has high torque to inertia ratio for gives low electrical and mechanical time constants.Its large thermal time constant ensures high stall torque capacity necessary during very low speed tracking application. Table 2 gives specifications of the servo motor.(Same type of motors are used for both the axes)

The torque load encountered at the output shaft of the gear boxes consists of three major components:(i)The wind force on the dish, (ii) inertia torque for the dish rotation and (iii) friction torque on the support system of the dish. Continuous torque specified for loads at the output of the elevation gear box is 11000 N-m and 25,400 N-m for azimuth at 40 Kmph wind speed.

5.0 TUNING AND INSTALLATION PROCEDURE:

The parameter tuning of control loops would decide over all system band width and the system performance.Since estimated value of LRF was around 1.5 Hz,overall desired system band width is of the order of 0.5 Hz.This banwidth should however allow control of wind induced disturbances.(This is to be confirmed by extensively testing the system performance in high wind conditions.)

Velocity and Torque loop have hard wired compensators ensuring that poles of both the loops lie far away from the desired system bandwidth.

Hence these loops need no tuning.(The current loop bandwidth is around 100 Hz and velocity loop band width is around 3 Hz)

Choice of the compensator parameters is governed by two conflicting requirements on the value of the system bandwidth:i>The bandwidth should be sufficiently lower than the system resonant frequency (also known as Locked Rotor Frequency or LRF).This would heavily attenuate signals close to the LRF and phase lags at these frequencies would not introduce instability.ii>Position loop bandwidth should be large enough to correct errors introduced due to wind caused disturbances.

Following steps are adopted to tune the position loop:

(i) Frequency response of the velocity loop is obtained by plotting tacho response to sinusoidal inputs.This gives the Locked Rotor Frequency (LRF) of the antenna axis and enables determination of bandwidth for velocity loop.The LRF is characterised by a distinct dip in the tacho output.

(ii) A lead compensator as described by Eq 1. is designed to achieve position loop bandwidth much less than the LRF.Section 5.1 briefly outlines the philosophy employed for setting the compensator parameters.

The ratio of LRF and the system bandwidth is generally decided on the basis of field experience.(A more analytical design procedure could be adopted by modelling the velocity loop taking into account LRF. With the simplified model shown in Fig. 7 a trial and error approach is adopted for achieving the required bandwidth.)

(iii) Step response of position loop is obtained by giving position step commands of different amplitude steps. Lower position loop bandwidth would make the system sluggish where as higher bandwidth would make the system produce large overshoots and oscillatory behaviour. Fine tuning of the parameters is done to obtain an acceptable response.

5.1 Setting the Parameters of the Lead Compensator:

Since the velocity loop bandwidth would be at least a factor of 4 or higher than the position loop band width, it could be approximated by a constant Kr for the low frequencies which lie within the position loop of band width. This constant can be determined experimentally by observing speed of the antenna in Arcmin/Sec for 1 Volt input to the rateloop. Fig 7 shows the simplified block diagram of the position loop. This reduces the design problem of a lead compensator to obtain adequately stable system giving the desired band width. The design can be carried out by plotting the open loop frequency response on a Bode plot and reading the corresponding the closed loop values from the Nichol's Chart [3].

Open loop Transfer Function of the position loop is given by

$$Gpo(s) = [Kr\ G_{22}(1+T_{21}s)/s^2(1+T_{23}s)] \qquad \ldots\ldots\ldots\ldots 2$$

6.0 A CASE STUDY FOR TUNING THE POSITION LOOP PARAMETERS.

What follows is the procedure for tuning and test results obtained during installation of the prototype servo system installed for the first antenna of GMRT.

6.1 LRF for azimuth axis was found to be 1.11 Hz and that for the elevation axis was found to be 1.43 Hz.Velocity loop bandwidth for both the axis was 3 Hz.

Hence the lead compensators for both the axes were designed for following specifications:

i)Position loop bandwidth to be adjusted at half the LRF value (0.55 Hz for Az axis and 0.7 Hz for El axis)
ii)Settling time less than 10 seconds.
iii)Over shoot less than 40 %
iv) Pointing and tracking accuracy of the order of 1/2 arc min

(These values have been found to give acceptable positioning performance to the user)

(Note that for GMRT steady state performance giving good pointing and tracking accuracy is much more important than the transient response)
Compensator for El was designed to give the open loop transfer function

$$G_{po}(s) = \frac{1.5(1+2.5s)}{s^{2}(1+0.25s)} \qquad \ldots\ldots\ldots\ldots 3$$

Using Nichol's chart technique it can be varified that the closed loop bandwidth obtained is 0.75 Hz.With these values,40 % overshoot was obtained giving a settling time of six second for a 5 arc min step.

Maximum error during tracking witnessed was 1/2 arcmin.(Different tracking speeds in the specified range as shown in Table 1 were tried)

Compensator for azimuth axis was designed to give the open loop transfer function

$$G_{po}(s) = \frac{1.2\,(1+1.5s)}{s^{2}\,(1+0.25s)} \qquad \ldots\ldots\ldots\ldots 4$$

Using Nichol's chart technique it can be varified that the closed loop bandwidth obtained is 0.59 Hz.However with these values the system behaviour was found oscillatory hence it was decided to shift the bandwidth further away from the LRF value by adjusting it's value at around 0.25Hz even at the expense of slowing down the system.This was achieved by designing the compensator to give an open loop transfer function of

$$Gpo(s) = \frac{0.24(1+4.26s)}{s^{2}(1+0.4s)} \qquad \ldots\ldots\ldots 5$$

This resulted in an absolutely stable system behaviour giving an overshoot of 36% and settling time of around 8 seconds.The pointing and tracking accuracy was 1/2 arc min .

The proto type system is working satisfactorily for the past one year giving acceptable tracking and pointing aperformance for the users.Two more antennas have been installed using the same tuning procedure and are functioning satisfactorily.

References:

(1) G.Swarup,et al."The Giant Metre-wave Radio Telescope"Current Science,Vol 60,No.2,25 January 1991,pp 95 -105

(2) D.R.Wilson ,"Modern Practice in Servo Design "Pergamon Press,1970

(3) I.J.Nagrath and M.Gopal,"Control System Engineering".Wiley Eastern Limited,2nd Edition,1981

(4) C.H.Houpis and G.B.Lamont,"Digital Control Systems , Theory ,Hardware,Software",McGraw Hill Book Company,International Student Edition, 1985.

Table 1. Specification of the GMRT Servo System

Dish Movement	+ / - 270 Deg about Azimuth (Az) axis & + 15 Deg to + 110 Deg about Elevation (El) axis
Gear Reduction Ratio	18963 for Az and 25162 for El axis
Dish slewing speed	30 Deg/Min Az Axis 20 Deg/Min El Axis
Minimum Tracking speed	5arc Min/Min for both Az and El axis
Max Tracking speed	150 Arc min/min for Az axis and 15 arc Min/Min for El axis.
Tracking and Pointing	1 Arc Min rms for Wind speeds < 20 KMPH
Accuracy	Few arc min for wind speeds above 20 Kmph
Design wind speeds (at 10 m height)	:
Operation up to	40 Kmph
Slew upto	80 Kmph
Survival	133 Kmph

Table 2. Specifications of the Servo Motor

(Type: TT53810 .Make:M/sIndustrial Drives,USA)

MOTOR PARAMETERS		UNITS	VALUE
Horsepower		hp	8.5
Max Operating Speed		RPM	2250
Continuous Torque(stall) @40deg C Ambient		N-m	47
Peak Torque		N-m	111
Torque Sensitivity		N-m/Amp	0.56
Back Emf Constant		V/Krpm	59
DC resistance		Ohm	0.045
Inductance		mH	0.33
Time Constant	mech	msec	13.0
	elect	msec	5.1
Tacho Sensitivity		V/Krpm	17.0
Rotor Inertia		Kg-m^2	0.064
Thermal Time Constant		Min	144
Static Friction		N-m	1.9
Viscous Damping		N-m/Krpm	0.568

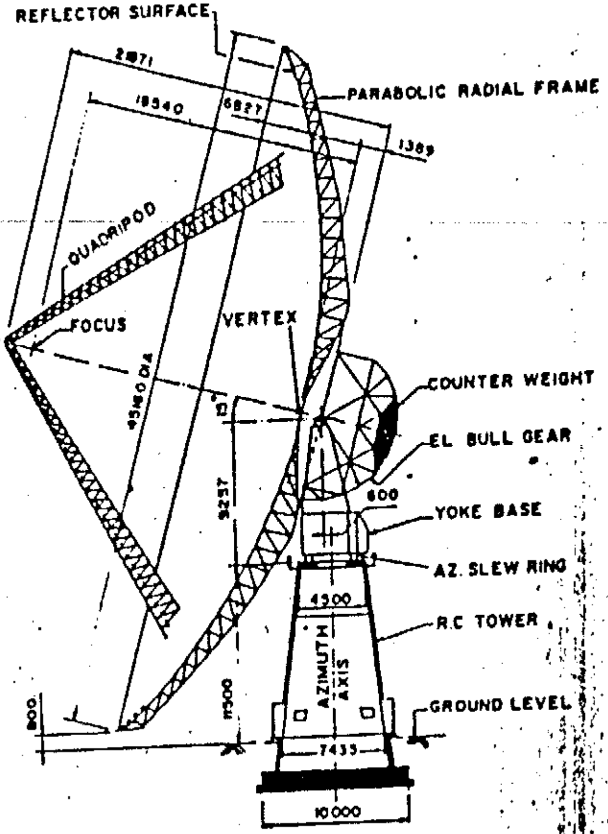


Figure 1. Sectional elevation of the parabolic dish.

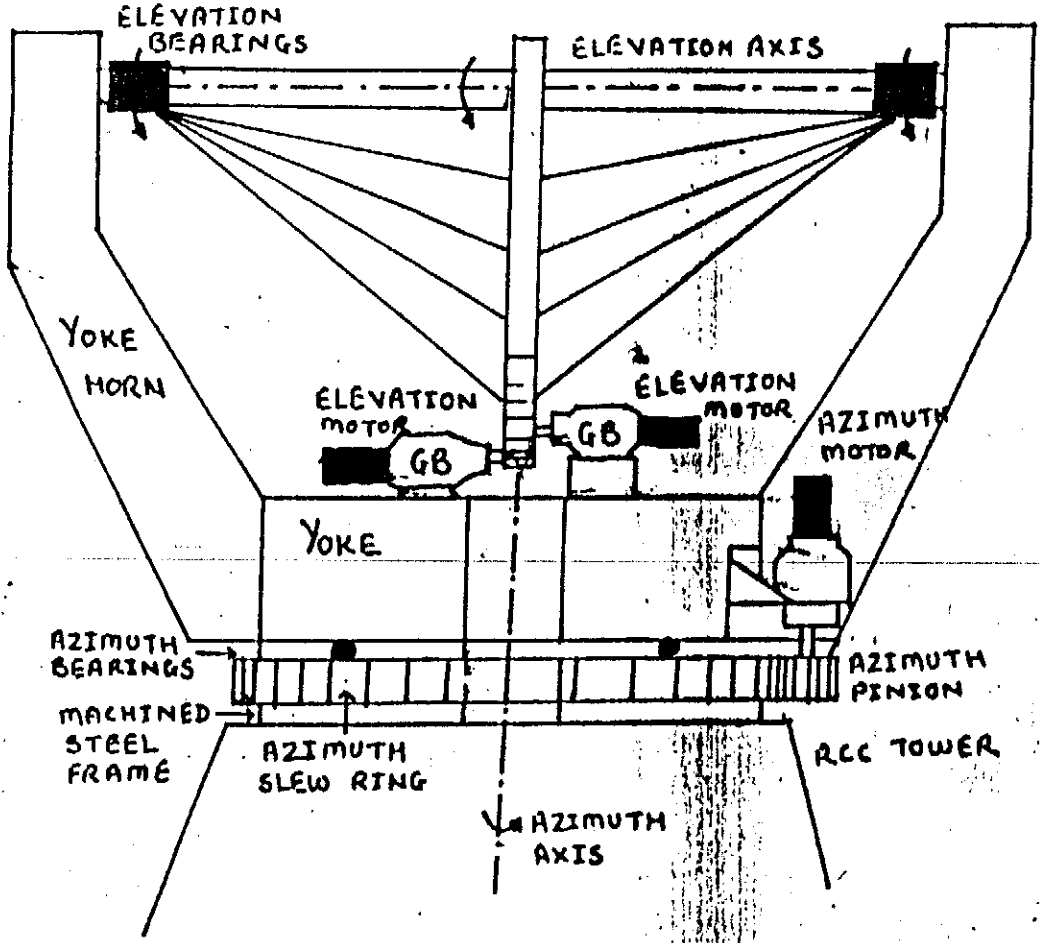


FIG.2. MECHANICAL DRIVE SYSTEM.

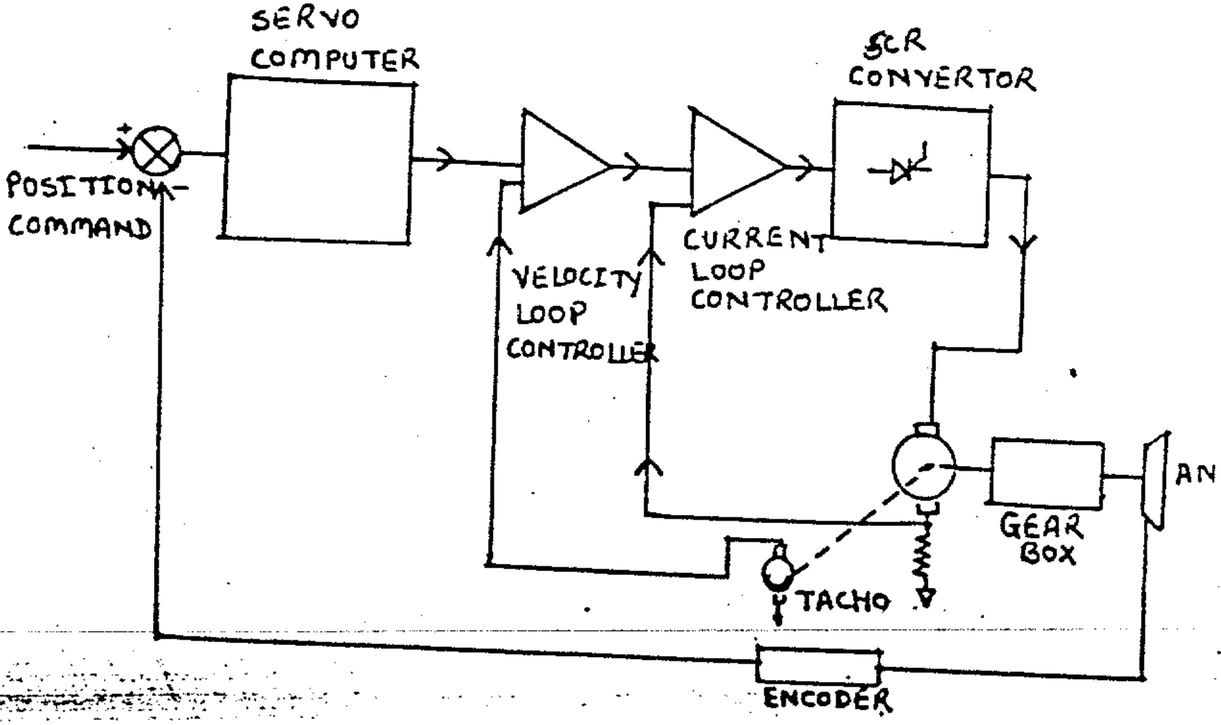


FIG.3 BASIC BLOCK DIAGRAM

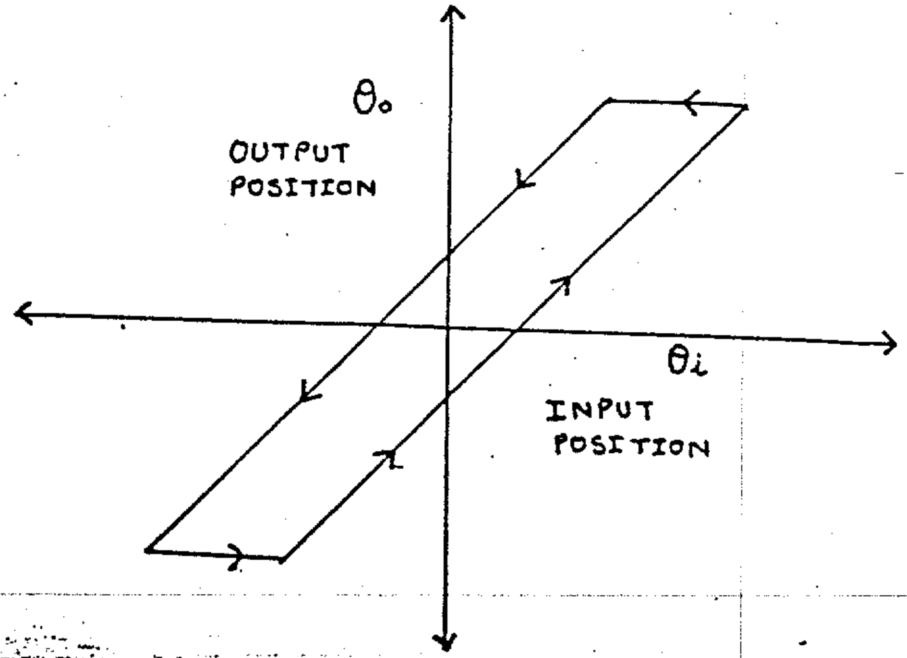


FIG. 4. DEAD-BAND EFFECT DUE TO BACKLASH.

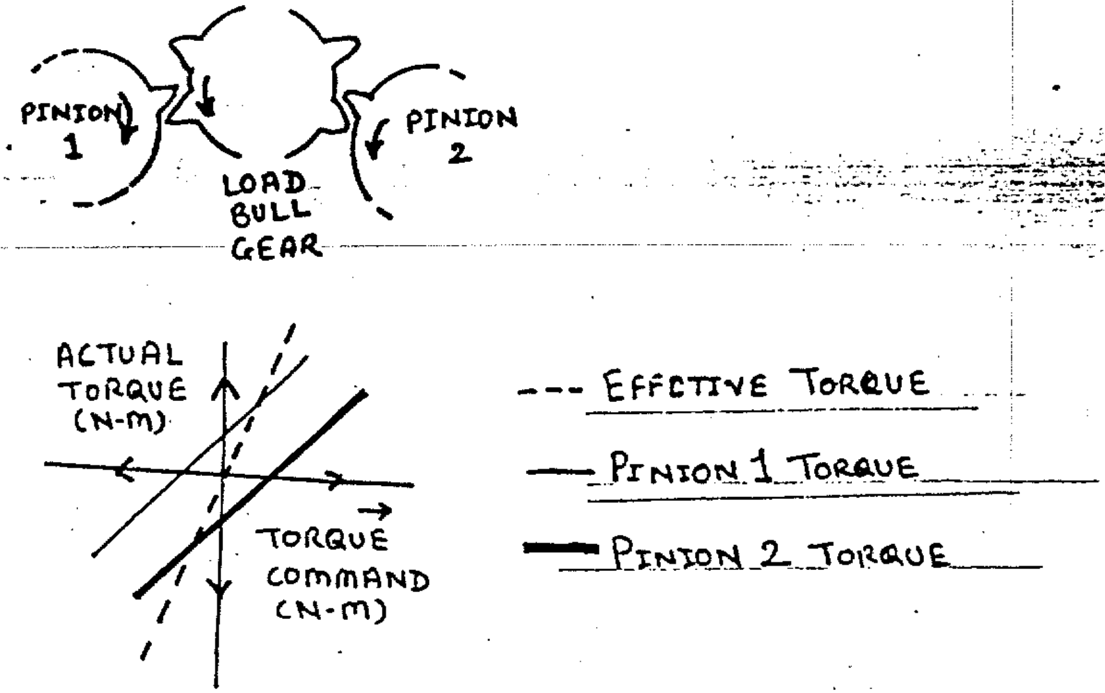


FIG. 5. CONCEPT OF COUNTER TORQUING.

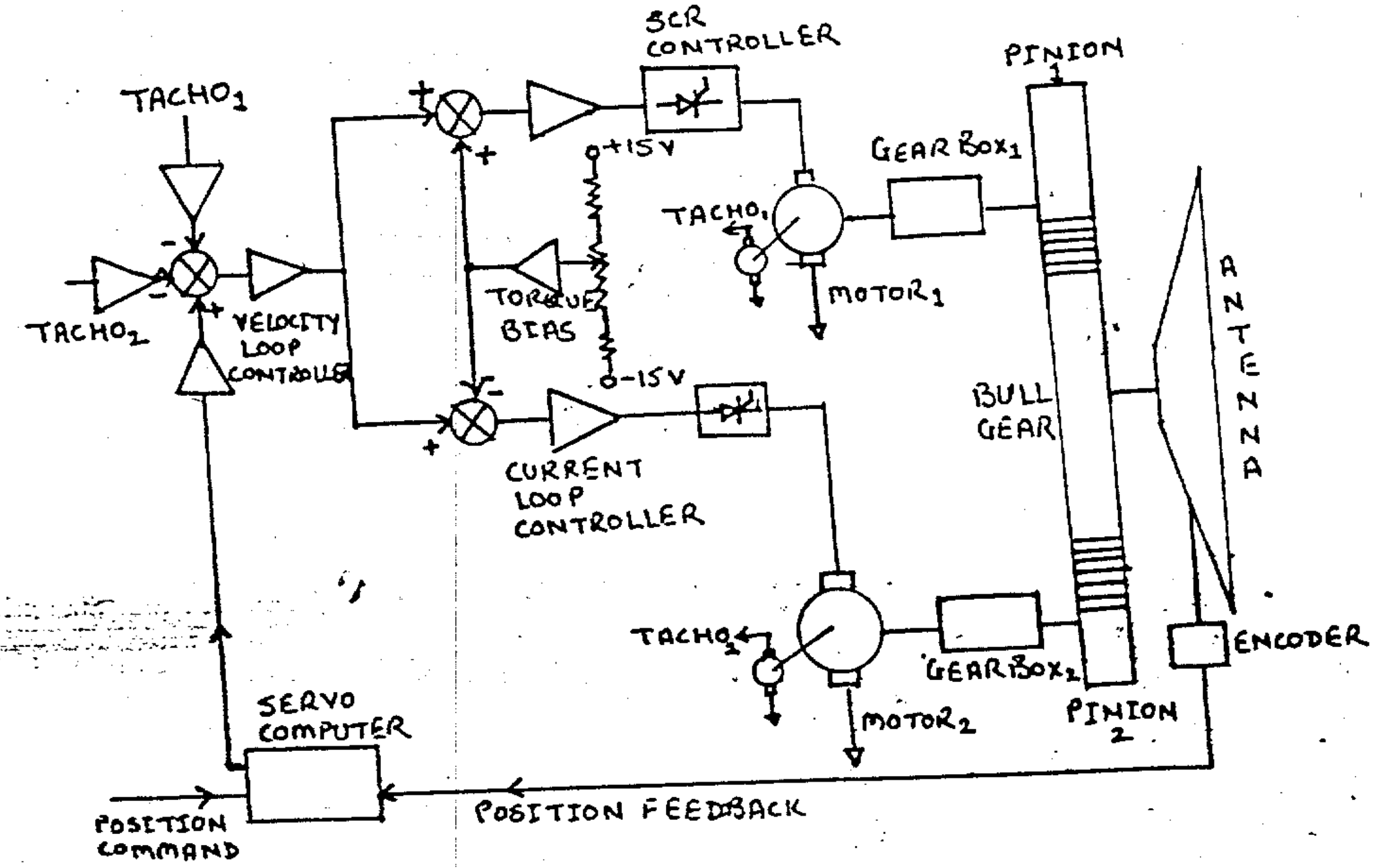
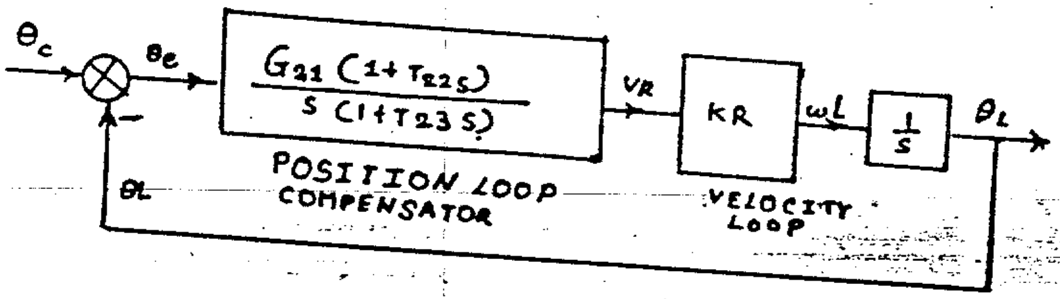


FIG. 6. GMRT CONTROL SYSTEM

DETAIL BLOCK DIAGRAM.



θ_c = COMMANDED ANGLE [ARC MIN]

VR = VELOCITY COMMAND [VOLTS]

θ_L = ANGULAR POSITION OF THE ANTENNA [ARC MIN]

WL = ANTENNA VELOCITY [ARC MIN/SEC]

θ_e = POSITION ERROR [ARC MIN]

KR = VELOCITY LOOP GAIN [ARC MIN/SEC/VOLTS]

FIG. 7. SIMPLIFIED BLOCK DIAGRAM FOR TUNING POSITION LOOP PARAMETERS.